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Using DSP Technology to Simplify Deep Space Ranging[1]

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Abstract—Commercially available Digital Signal Processor (DSP) technology has enabled a new spacecraft ranging design. The new design eliminates custom correlator printed circuit boards in favor of COTS DSPs. This reduces overall size, parts count, and complexity. Embedded DSP software will provides the flexibility to handle Pseudo-Random Noise, sequential squarewave, or other periodic ranging tones. The design implementation will also meet the Jet Propulsion Laboratory (JPL) requirements for both near-Earth and deep space ranging.

JPL's Network Simplification Project will consolidate the Deep Space Network (DSN) ground systems functions into less hardware and simplify network operations. This effort includes implementing the new spacecraft ranging design described here. This implementation will reduce the amount of ranging hardware (and thus maintenance) while increasing the operational flexibility. The new ranging implementation also provides a new DSN capability to support the new Spacecraft Transponding Modem [1] being developed at JPL.

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1. INTRODUCTION

The current DSN ranging capability uses the Sequential Ranging Assembly (SRA) to produce a series of squarewave tones. The SRA can set the lowest frequency tone based on the desired ranging ambiguity resolution. However, the SRA does not provide any other type of ranging tones. The regenerative ranging capability of the STM uses a Pseudo-random Noise (PN) ranging tone. Upgrading the SRA to support the STM PN tones is not feasible because the SRA implementation is based on 1980's technology, using custom wire-wrapped printed circuit boards (PCB) and a CPU with outdated clock speed and memory.

The Network Simplification Project (NSP) is implementing a new ranging capability. The "half rack" (2'x 2' x 3') of SRA custom equipment and CPU will be replaced by 2 VME cards in the receiver, an identical set of 2 VME cards in the transmitter, and software incorporated into the receiver and transmitter controllers. The goal is to reduce the amount of DSN hardware, reduce the number of subsystem interfaces, and provide a simpler system. The new ranging capability is also simpler to operate and calibrate, with several ranging functions now automated within the receiver and exciter controllers.

The NSP ranging implements the tone generation in software and therefore is readily extensible to producing other ranging tones. The NSP ranging design has been extended from squarewave tones to handle STM PN tones and several related patterns. By extending the NSP ranging design now, we hope to provide a robust capability to handle ranging requirements that may be called for in the future.

2. DESCRIPTION OF DSN RANGING

Design Requirements

The requirements for DSN ranging specify the ability to measure the round trip light time (RTLT) to a spacecraft to a accuracy of around 2 meters, assuming enough ranging signal power. The ranging system must function for signals from +50 dB-Hz to –10 dB-Hz, and preferably function at even lower power levels. The RTLT can be 10 to 100 Astronomical Units, so the ranging measurement must be able to resolve ambiguities up to 157,000 km. The ranging system must also provide a means to measure the ranging signal delay through the ground equipment. This 'ranging calibration' measurement includes the cables to and from the antenna front end.

[1] 0-7803-6599-2/01/$10.00 © 2001 IEEE

These requirements reflect a need to support ranging for near-Earth and deep space missions. Implementing a ranging system that supports high-power, low RTLT missions while also meeting the needs of much lower-power, large RTLT missions has been an ongoing challenge for the DSN and JPL.

The current DSN ranging capability uses the SRA to produce a series of squarewave tones with the highest frequency tone at approximately 1 MHz [2]. Each subsequent tone is half the frequency of the preceding tone, down to an approximate 1 Hz squarewave. Tones below 16 KHz are chopped with the original 1 MHz tone. These tones are phase-modulated onto the uplink carrier sent to the spacecraft. The SRA allows the spacecraft navigation team to specify the lowest frequency tone based on the desired ranging ambiguity resolution. The SRA also controls the duration of each tone, and thus the total "cycle time" to produce each range measurement.

The spacecraft de-modulates the ranging tones from the uplink carrier, passes them through a 1.5 MHz low-pass filter, then re-modulates the tones onto the downlink carrier. After a complete RTLT, the ranging tones are demodulated from the downlink carrier by the DSN receiver and passed back to the SRA. The SRA correlates the received tones against the transmitted tones, integrates the In-phase and Quadrature correlation values, then determines the phase of the received tone relative to the transmitted tone. This phase delay is published as the ranging measurement.

Current DSN implementation

The schematic in Figure 1 shows how the SRA implementation (the Old System) relied on custom hardware to accomplish most of these functions. The programmable software part of the SRA is limited to periodically sampling the I and Q values, and the user interface. The correlation function is implemented in hardware and can only produce and correlate sequential squarewaves tones.

New NSP implementation

The NSP ranging (Figure 1's New System) will replace the SRA with 2 VME cards (a commercial DSP and an interface card) in the transmitter, an identical set of 2 VME cards in the receiver, and software incorporated into the receiver and transmitter controllers. This eliminates the "half rack" (2'x 2' x 3') of SRA custom equipment and CPU.

The new NSP ranging design uses current DSP technology to implement most of the ranging function is software. This design has 2 primary advantages: 1) It reduces the amount of custom hardware, 2) It can support many different types of range tones. This design was developed in 1987 at JPL [3] [4] but it's implementation had to wait until COTS DSP processing speed and FIFO technology reached current levels. The 1 MHz ranging tone requires FIFOs capable of at least 4 Megasamples/sec in order to obtain quadrature values. The NSP implementation uses DSP's FIFOs that run at 16 Megasamples/sec. Besides meeting the requirement, this provides a way to support 4 MHz ranging tones if such tones become a requirement. The commercial DSP has 4

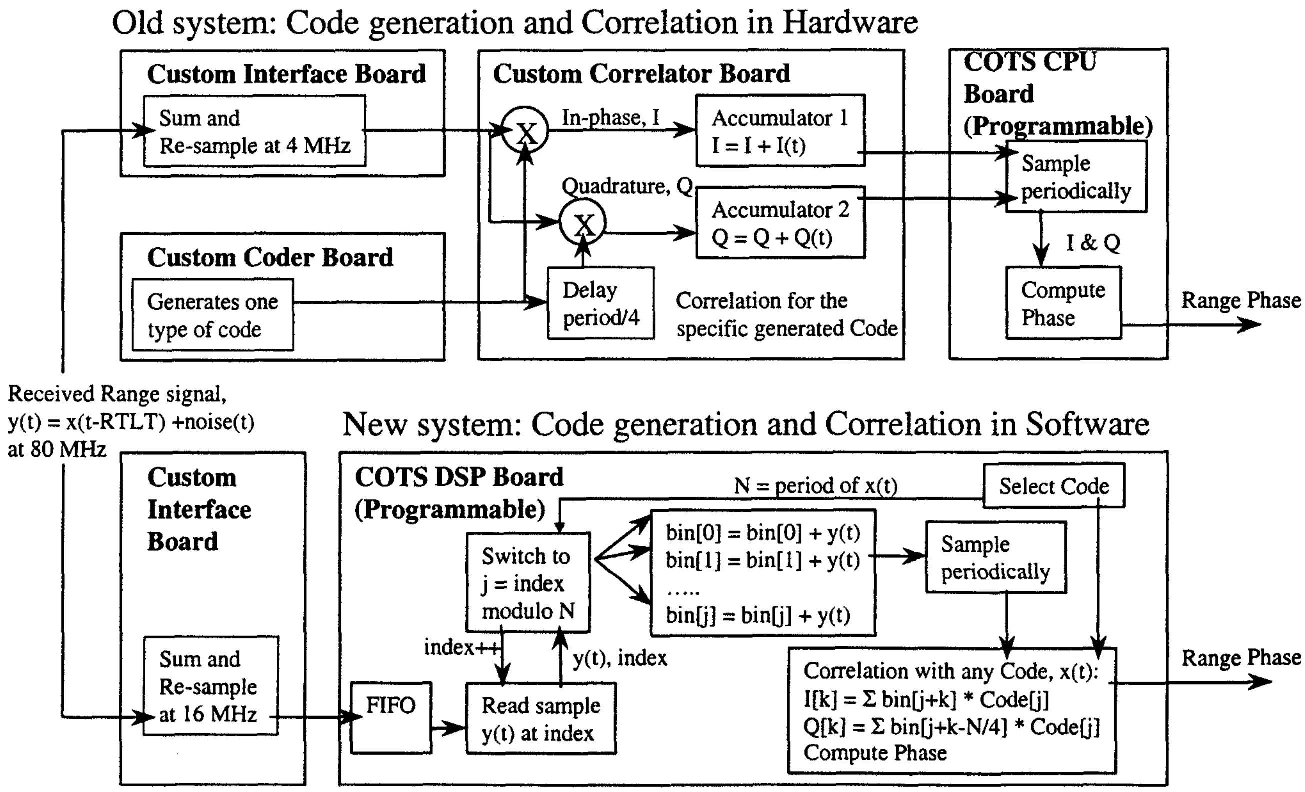

Figure 1 Comparison of ranging implementations

TMS320C6201 processors made by TI. Each CPU has a clock speed of 200 MHz and the potential to pipeline at execute up to 8 instructions per clock cycle.

The NSP dedicating 1 processor to managing the inbound FIFO, each sample is accumulated to a specific location in an accumulator array (Figure 1's 'bin[j]'). During this accumulation process, the only value specific to the type of range pattern is the number, N, of samples per 1 complete cycle of the pattern. The software integrates the ranging signal by adding each sample, Yj to bin[j mod N]. Since the range pattern repeats every N samples, each bin[j] element is the sum of values at the same phase, j/N, of the pattern.
After integrating for a specified time, the bin[j] values are sampled and correlated against the expected ranging tone pattern. Since the correlation is done by the software, this correlation process can be programmed for a variety of different range tones. The only limitations on range tones are memory considerations and the 4 MHz limit imposed by the FIFOs.

The Network Simplification Project requires that the new ranging implement the existing sequential tone capability and provide PN tone capability. The NSP ranging implementation must specifically cover the PN pattern used for regenerative ranging on the STM. However, the NSP ranging design will allow for a variety of PN tone combinations that includes the STM pattern.

3. PN VERSUS SEQUENTIAL RANGING

The advantages of PN range tones over sequential tone for the regenerative ranging purpose are described in [1]. In brief, the PN tones repeat endlessly once transmission is started at time T0. But the Sequential tones require transmitting different tones depending on the number of seconds past transmission start time, T0. Receiving the Sequential tones requires knowing a priori the RTLT to within 1 second, the chosen highest and lowest frequency tones, the chosen duration interval of the tones, and the chopping method selected.

For the STM regenerative ranging application, it was desirable for the spacecraft to require minimal knowledge of the ground system configuration. The STM also needed a robust scheme for integrating the ranging signal to acquire sufficient ranging power to noise. At a minimum, the Sequential tones would require the STM to process and apply an RTLT estimate from the uplink commands.

The PN tone pattern chosen for the STM regenerative ranging application only requires that the STM 'know' the pattern to expect. The STM can begin its accumulation at any random phase of the pattern. Since the pattern repeats itself after N samples, or 'chips', the STM can select how many cycles of the pattern to integrate before making a range determination. The specific pattern chosen for STM is a logical ANDing of PN codes of lengths 7, 11, 15, 19, and 23. The resulting pattern of length 504,735 'chips' is then ORed with a 'clock' squarewave of +1 chip, -1 chip, creating a pattern of total length 1,009,470 chips. The STM ranging pattern has several desirable features:

1) Most of the range tone power is in the highest frequency 'clock' component. This provides the most power to the tone used for the high precision range resolution measurement.
2) The rest of the tone has the spread-spectrum characteristics of PN signals, allowing it to occupy a large amount of frequency without interfering with other signals. This allows the low-frequency ambiguity-resolving part of the range tone to coexist the other spacecraft subcarriers. On the uplink side, the commanding subcarrier and symbols may see the slight increase of the noise floor due to the PN tones, but will not see any accumulated power from the PN tones. The same for the telemetry on the downlink side.
3) The range tone can be correlated against the separate PN tones used in its creation. So the accumulator does not need 1,009,470 separate bins. Instead, the software can accumulate to 6 bins of lengths 2, 7, 11, 15, 19, and 23 chips.

The NSP requirements were extended to provide ground ranging system support for the STM PN range tones. Cross-participation early in the NSP design allows us to satisfy both the Sequential and STM PN requirements with a more general range tone framework.

4. EXTENSIBILITY OF NSP RANGING

For DSN ranging systems, flexibility has been the key to customer support and a long life for the subsystem. The more extensible the range tone generation and correlation process, the more likely the new NSP ranging will be able to meet future unpredicted requirements. This adaptability may save future software re-design and development costs.

With this design philosophy in mind, the NSP ranging system has been designed to produce a multitude of range tones. The software design divides range tones into three categories: Sequential, Generated PN, Auxiliary.

Sequential Tones

Sequential tones are characterized by their changing as a function of time. Instead of 1 pattern being produced, the pattern changes from one tone to the next tone in the sequence at specified time intervals. Typically, the first tone in the sequence is a squarewave at approximately 1 MHz, called the 'clock' frequency. The exact 'clock' frequency is determined by uplink carrier frequency. The range tones are produced at a ratio of the uplink carrier and are coherent with the carrier. After an interval of T1+1 seconds, the ranging system produces another squarewave tone at ½ the 'clock' frequency. This tone is generated for T2+1 seconds. This continues with each tone at ½ the frequency of the previous tone and lasting for T2+1 seconds. The low frequency tones below 1 KHz are ANDed with a copy of the original 'clock' tone to produce a 'chopped' signal near 1 MHz. The original reason for using a sequence of tones was that the implementation would require only 2 correlators: 1for In-phase and 1 for Quadrature. The 2 correlators could be re-configured for each tone that appeared in the sequence. The SRA implementation uses 2 custom hardware correlators. It accumulates the I and Q values for T1 (or T2) seconds, then re-configures the correlators and accumulators during the 1 second interval. This was not the most efficient use of time, but it made the SRA hardware implementation possible.

The new NSP ranging software exactly reproduces the sequence produced by the SRA. Using the same timing reference the SRA uses, the NSP ranging keeps track of Sequential tone generation and correlation in the same sequence as the SRA. Testing has confirmed that a sequence of range tone generated by an SRA can be correlated and measured by the downlink NSP ranging hardware and obtain a correct result.

Generated PN Tones

The primary characteristic of the PN Tones is that there is only 1 pattern that repeats after N 'chips'. The STM ranging tone fits into a class of PN tones that are generated as logical combinations of shorter tones. If the user selects the STM pattern, the uplink ranging software generates and stores all 1,009,470 chips and manages their output to a FIFO and Digital to Analog converter. The receiving ranging software can not accumulate the entire 1,009,470 chip pattern due to memory and speed limitations. Like the STM, the NSP ranging software accumulates and correlates based on the shorter PN tones used in the overall pattern. The NSP ranging implementation for the STM range tones uses 2 accumulator bins of length 7*11*15=1155 and 2*15*19=874 chips. This allows the ground ranging system to pick up more of the ranging power in the intermodulation products of the PN tones.

The interface for the new NSP ranging system allows the user to select the STM pattern, or specify another combination of PN tones. For example, the STM pattern is specified in a table that defines each tone's pattern and length. The table also specifies the logical combination of tones to produce the overall pattern. A user has the option of specifying different tones, or using fewer tones to produce a shorter pattern. This may prove desirable for non-regenerative ranging where the PN spread spectrum characteristics are desired, but shorter pattern length is needed. During the same integration time, a shorter pattern will repeat many more times than the long STM pattern, giving more signal to noise ratio (SNR) in each chip. If the spacecraft location is known to some accuracy, the user can trade the ambiguity resolving power of a long pattern to get the higher chip SNR of a shorter pattern.

Auxiliary Tones

A simple extension of the NSP ranging software design provides the capability for the user to specify the entire range tone pattern. The software is instructed to read the pattern from a file instead of generating the pattern. However, the software still stores the pattern chips in memory and manages their output to a FIFO and Digital to Analog converter, exactly the same as the Generated PN case. The software has a limit of 2^{20} = 1,048,576 chips on the uplink side. On the downlink side of the NSP ranging system, memory and speed limitations will not allow for accumulating the entire 2^{20}-chip pattern. The software can accumulate up to 2048 chips of any pattern. If the Auxiliary pattern has a sub-component with a periodicity, $N \leq 2048$, the software can accumulate into buffers of length N and recover more of the ranging signal.

5. IMPLEMENTATION STATUS

Successful stand-alone tests of the NSP ranging hardware and software have been conducted for both uplink and downlink components. This included verification of the Sequential tone capability using an existing DSN SRA. Currently the ranging hardware and software is being integrated with the consolidated controllers of the receiver and the uplink exciter. In December, 2000 we expect to test the NSP ranging Generated PN tone capability with the first unit of the STM. Integration, testing, and system verification of the NSP will conclude with the start of installations to the DSN in June, 2003.

6. CONCLUSION

This paper provides a description of the current DSN deep space ranging capability and the additional ranging capabilities to be provided by the NSP. The NSP design will also provide for extensions of the ranging capabilities to new range tones. An attempt was made to anticipate future needs of the ranging user community and design the new ranging system with the flexibility to meet those needs. Any feedback from potential users of deep space ranging is encouraged.

7. REFERENCES

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8. ACKNOWLEDGEMENTS

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__Scott Bryant__ is a member of the senior staff at the Jet Propulsion Laboratory. He has a bachelor's in Aeronautics and Astronautics Engineering from MIT and has worked in the aerospace industry for the last 13 years. He has worked on several of JPL's Deep Space Network (DSN) systems since 1990 including the receivers, exciters, and spacecraft tracking subsystems. He has been principally involved with software design and development for spacecraft tracking, including holding the position of cognizant design engineer for the current DSN Sequential Ranging Assembly. Scott is currently the implementation and design lead for the spacecraft tracking and ranging portion of JPL's Network Simplification Project. He is coordinating commercial DSP vendors, JPL hardware specialists, and the system design to produce a deep space ranging system that is fully integrated with the DSN receiver and transmitter subsystems.